

# CHAPTER 13

## MEIOSIS AND SEXUAL LIFE CYCLES

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### OUTLINE

- I. An Introduction to Heredity
  - A. Offspring acquire genes from parents by inheriting chromosomes
  - B. Like begets like, more or less: a comparison of asexual versus sexual reproduction
- II. The Role of Meiosis in Sexual Life Cycles
  - A. Fertilization and meiosis alternate in sexual life cycles
  - B. Meiosis reduces chromosome number from diploid to haploid: *a closer look*
- III. Origins of Genetic Variation
  - A. Sexual life cycles produce genetic variation among offspring
  - B. Evolutionary adaptation depends on a population's genetic variation

### OBJECTIVES

After reading this chapter and attending lecture, the student should be able to:

1. Explain why organisms only reproduce their own kind, and why offspring more closely resemble their parents than unrelated individuals of the same species.
2. Explain what makes heredity possible.
3. Distinguish between asexual and sexual reproduction.
4. Diagram the human life cycle and indicate where in the human body that mitosis and meiosis occur; which cells are the result of meiosis and mitosis; and which cells are haploid.
5. Distinguish among the life cycle patterns of animals, fungi, and plants.
6. List the phases of meiosis I and meiosis II and describe the events characteristic of each phase.
7. Recognize the phases of meiosis from diagrams or micrographs.
9. Describe the process of synapsis during prophase I, and explain how genetic recombination occurs.
10. Describe key differences between mitosis and meiosis; explain how the end result of meiosis differs from that of mitosis.
11. Explain how independent assortment, crossing over, and random fertilization contribute to genetic variation in sexually reproducing organisms.
12. Explain why inheritable variation was crucial to Darwin's theory of evolution.
13. List the sources of genetic variation.

**KEY TERMS**

heredity	karyotype	zygote	meiosis II
variation	homologous	diploid cells	synapsis
genetics	chromosomes	meiosis	tetrad
gene	sex chromosomes	alternation of	chiasmata
asexual reproduction	autosome	generations	chiasma
clone	gamete	sporophyte	crossing over
sexual reproduction	haploid cell	spores	
life cycle	fertilization	gametophyte	
somatic cell	syngamy	meiosis I	

**LECTURE NOTES**

Reproduction is an emergent property associated with life. The fact that organisms reproduce their own kind is a consequence of heredity.

*Heredity* = Continuity of biological traits from one generation to the next

- Results from the transmission of hereditary units, or *genes*, from parents to offspring.
- Because they share similar genes, offspring more closely resemble their parents or close relatives than unrelated individuals of the same species.

*Variation* = Inherited differences among individuals of the same species

- Though offspring resemble their parents and siblings, they also diverge somewhat as a consequence of inherited differences among them.
- The development of *genetics* in this century has increased our understanding about the mechanisms of variation and heredity.

*Genetics* = The scientific study of heredity and hereditary variation.

Beginning students often compartmentalize their knowledge, which makes it difficult to transfer and apply information learned in one context to a new situation. Be forewarned that unless you point it out, some students will never make the connection that meiosis, sexual reproduction, and heredity are all aspects of the same process.

**I. An Introduction to Heredity****A. Offspring acquire genes from parents by inheriting chromosomes**

*DNA* = Type of nucleic acid that is a polymer of four different kinds of nucleotides.

*Genes* = Units of hereditary information that are made of *DNA* and are located on *chromosomes*.

- Have specific sequences of nucleotides, the monomers of DNA
- Most genes program cells to synthesize specific proteins; the action of these proteins produce an organism's inherited traits.

Inheritance is possible because:

- DNA is precisely replicated producing copies of genes that can be passed along from parents to offspring.
- Sperm and ova carrying each parent's genes are combined in the nucleus of the fertilized egg.

The actual transmission of genes from parents to offspring depends on the behavior of *chromosomes*.

**Chromosomes** = Organizational unit of heredity material in the nucleus of eukaryotic organisms

- Consist of a single long DNA molecule (double helix) that is highly folded and coiled along with proteins
- Contain genetic information arranged in a linear sequence
- Contain hundreds or thousands of genes, each of which is a specific region of the DNA molecule, or *locus*

**Locus** = Specific location on a chromosome that contains a gene

- Each species has a characteristic number of chromosomes; humans have 46 (except for their reproductive cells).

### B. Like begets like, more or less: a comparison of asexual versus sexual reproduction

Asexual Reproduction	Sexual Reproduction
Single individual is the sole parent.	Two parents give rise to offspring.
Single parent passes on <i>all</i> its genes to its offspring.	Each parent passes on <i>half</i> its genes, to its offspring.
Offspring are genetically identical to the parent.	Offspring have a unique combination of genes inherited from both parents.
Results in a <i>clone</i> , or genetically identical individual. Rarely, genetic differences occur as a result of <i>mutation</i> , a change in DNA (see Campbell, Figure 13.1).	Results in greater genetic variation; offspring vary genetically from their siblings and parents (see Campbell, Figure 13.2).

What generates this genetic variation during sexual reproduction? The answer lies in the process of meiosis.

## III. The Role of Meiosis in Sexual Life Cycles

### A. Fertilization and meiosis alternate in sexual life cycles

#### 1. The human life cycle

Follows the same basic pattern found in all sexually reproducing organisms; *meiosis* and *fertilization* result in alternation between the haploid and diploid condition (see Campbell, Figure 13.3).

**Life cycle** = Sequence of stages in an organism's reproductive history, from conception to production of its own offspring

**Somatic cell** = Any cell other than a sperm or egg cell

- Human somatic cells contain 46 chromosomes distinguishable by differences in size, position of the centromere, and staining or banding pattern.
- Using these criteria, chromosomes from a photomicrograph can be matched into *homologous* pairs and arranged in a standard sequence to produce a karyotype.

**Karyotype** = A display or photomicrograph of an individual's somatic-cell metaphase chromosomes that are arranged in a standard sequence. (See Campbell, Methods Box: *Preparation of a Karyotype*)

- Human karyotypes are often made with lymphocytes.
- Can be used to screen for chromosomal abnormalities

**Homologous chromosomes (homologues)** = A pair of chromosomes that have the same size, centromere position, and staining pattern.

- With one exception, homologues carry the same genetic loci.

- Homologous *autosomes* carry the same genetic loci; however, human *sex chromosomes* carry different loci even though they pair during prophase of meiosis I.

*Autosome* = A chromosome that is not a sex chromosome.

*Sex chromosome* = Dissimilar chromosomes that determine an individual's sex

- Females have a homologous pair of X chromosomes.
- Males have one X and one Y chromosome.
- Thus, humans have 22 pairs of autosomes and one pair of sex chromosomes.

Chromosomal pairs in the human karyotype are a result of our sexual origins.

- One homologue is inherited from each parent.
- Thus, the 46 somatic cell chromosomes are actually two sets of 23 chromosomes; one a maternal set and the other a paternal set.
- Somatic cells in humans and most other animals are *diploid*.

*Diploid* = Condition in which cells contain two sets of chromosomes; abbreviated as  $2n$

*Haploid* = Condition in which cells contain one set of chromosomes; it is the chromosome number of *gametes* and is abbreviated as  $n$

*Gamete* = A haploid reproductive cell

- *Sperm cells* and *ova* are gametes, and they differ from somatic cells in their chromosome number. Gametes only have one set of chromosomes.
- Human gametes contain a single set of 22 autosomes and one sex chromosome (either an X or a Y).
- Thus, the haploid number of humans is 23.

The diploid number is restored when two haploid gametes unite in the process of *fertilization*. Sexual intercourse allows a haploid sperm cell from the father to reach and fuse with an ovum from the mother.

*Fertilization* = The union of two gametes to form a *zygote*

*Zygote* = A diploid cell that results from the union of two haploid gametes

- Contains the maternal and parental haploid sets of chromosomes from the gametes and is diploid ( $2n$ )
- As humans develop from a zygote to sexually mature adults, the zygote's genetic information is passed with precision to all somatic cells by mitosis.

Gametes are the only cells in the body that are *not* produced by mitosis.

- Gametes are produced in the ovaries or testes by the process of *meiosis*.
- *Meiosis* is a special type of cell division that produces haploid cells and compensates for the doubling of chromosome number that occurs at fertilization.
- Meiosis in humans produces sperm cells and ova which contain 23 chromosomes.
- When fertilization occurs, the diploid condition ( $2n=46$ ) is restored in the zygote.

## 2. The variety of sexual life cycles

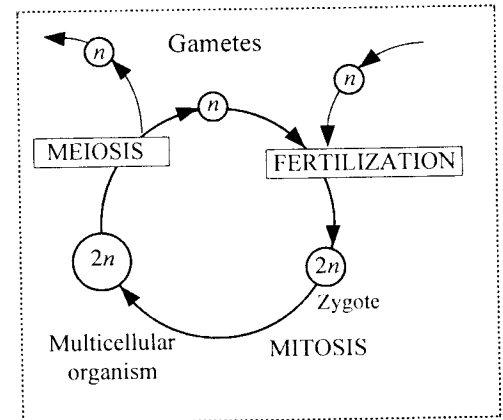
Alternation of meiosis and fertilization is common to all sexually reproducing organisms; however, the timing of these two events in the life cycle varies among species. There are three basic patterns of sexual life cycles (see Campbell, Figure 13.4):

### a. Animal

In animals, including humans,

gametes are the only haploid cells.

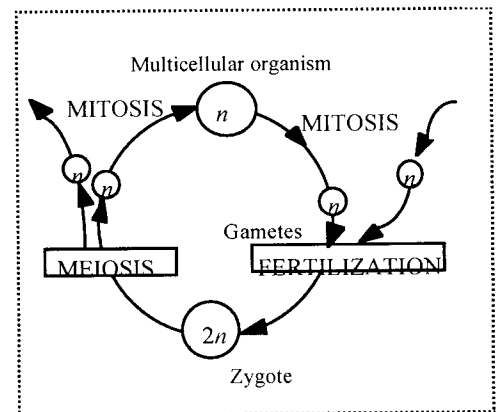
- Meiosis occurs during gamete production. The resulting gametes undergo no further cell division before fertilization.
- Fertilization produces a diploid zygote that divides by mitosis to produce a diploid multicellular animal.



#### b. Fungi and some protists

In many fungi and some protists, the only diploid stage is the zygote.

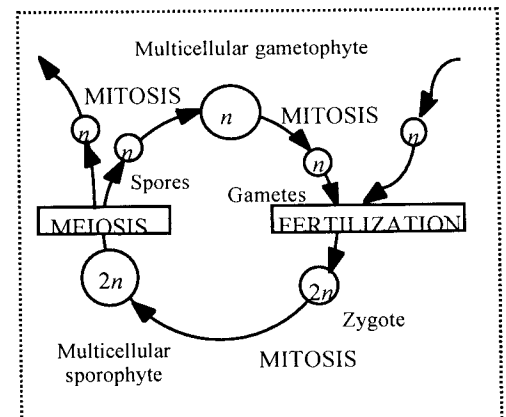
- Meiosis occurs immediately after the zygote forms.
- Resulting haploid cells divide by *mitosis* to produce a haploid multicellular organism.
- Gametes are produced by *mitosis* from the already haploid organism.



#### c. Plants and some algae

Plants and some species of algae alternate between multicellular haploid and diploid generations.

- This type of life cycle is called an *alternation of generations*.
- The multicellular diploid stage is called a *sporophyte*, or spore-producing plant. Meiosis in this stage produces haploid cells called *spores*.
- Haploid spores divide mitotically to generate a multicellular haploid stage called a *gametophyte*, or gamete-producing plant.
- Haploid gametophytes produce gametes by mitosis.
- Fertilization produces a diploid zygote which develops into the next sporophyte generation.



### B. Meiosis reduces chromosome number from diploid to haploid: a closer look

Meiosis and sexual reproduction significantly contribute to genetic variation among offspring.

Meiosis includes steps that closely resemble corresponding steps in mitosis (see Campbell, Figure 13.5).

- Like mitosis, meiosis is preceded by replication of the chromosomes.
- Meiosis differs from mitosis in that this single replication is followed by two consecutive cell divisions: *meiosis I* and *meiosis II*.

- These cell divisions produce *four* daughter cells instead of two as in mitosis.
- The resulting daughter cells have *half* the number of chromosomes as the original cell; whereas, daughter cells of mitosis have the same number of chromosomes as the parent cell.
- Campbell, Figure 13.6 shows mitosis and meiosis in animals.

The stages of meiotic cell division:

*Interphase I.* Interphase I precedes meiosis.

- Chromosomes replicate as in mitosis.
- Each duplicated chromosome consists of two identical sister chromatids attached at their centromeres.
- Centriole pairs in animal cells also replicate into two pairs.

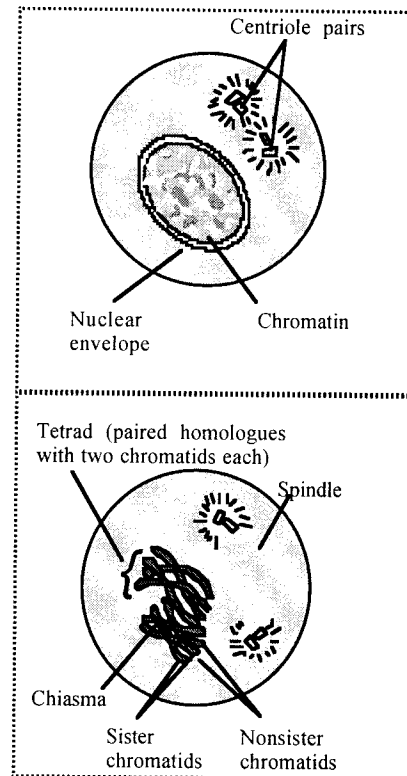
*Meiosis I.* This cell division segregates the two chromosomes of each homologous pair and reduces the chromosome number by one-half. It includes the following four phases:

*Prophase I.* This is a longer and more complex process than prophase of mitosis.

- Chromosomes condense.
- *Synapsis* occurs. During this process, homologous chromosomes come together as pairs.
- Chromosomes condense further until they are distinct structures that can be seen with a microscope. Since each chromosome has two chromatids, each homologous pair in synapsis appears as a complex of four chromatids or a *tetrad*.
- In each tetrad, sister chromatids of the same chromosome are attached at their centromeres. Nonsister chromatids are linked by X-shaped *chiasmata*, sites where homologous strand exchange or *crossing-over* occurs.
- Chromosomes thicken further and detach from the nuclear envelope.

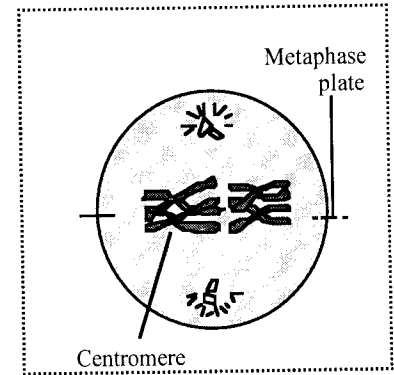
As prophase I continues, the cell prepares for nuclear division.

- Centriole pairs move apart and spindle microtubules form between them.
- Nuclear envelope and nucleoli disperse.
- Chromosomes begin moving to the metaphase plate, midway between the two poles of the spindle apparatus.
- Prophase I typically occupies more than 90% of the time required for meiosis.



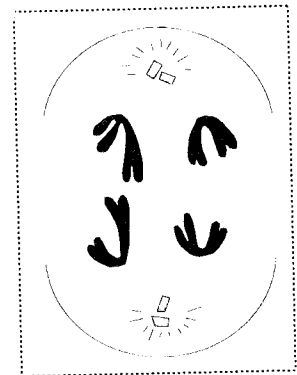
*Metaphase I.* Tetrads are aligned on the metaphase plate.

- Each synaptic pair is aligned so that centromeres of homologues point toward opposite poles.
- Each homologue is thus attached to kinetochore microtubules emerging from the pole it faces, so that the two homologues are destined to separate in anaphase and move toward opposite poles.



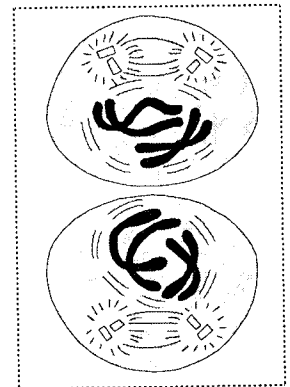
*Anaphase I.* Homologues separate and are moved toward the poles by the spindle apparatus.

- Sister chromatids remain attached at their centromeres and move as a unit toward the same pole, while the homologue moves toward the opposite pole.
- This differs from mitosis during which chromosomes line up individually on the metaphase plate (rather than in pairs) and sister chromatids are moved apart toward opposite poles of the cell.



*Telophase I and Cytokinesis.* The spindle apparatus continues to separate homologous chromosome pairs until the chromosomes reach the poles.

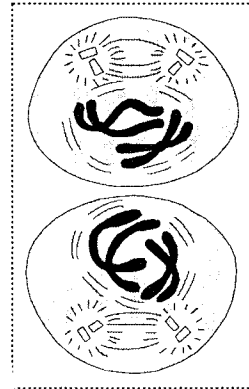
- Each pole now has a haploid set of chromosomes that are each still composed of two sister chromatids attached at the centromere.
- Usually, cytokinesis occurs simultaneously with telophase I, forming two haploid daughter cells. *Cleavage furrows* form in animal cells, and cell plates form in plant cells.
- In some species, nuclear membranes and nucleoli reappear, and the cell enters a period of *interkinesis* before meiosis II. In other species, the daughter cells immediately prepare for meiosis II.
- Regardless of whether a cell enters interkinesis, *no DNA replication occurs before meiosis II.*



**Meiosis II.** This second meiotic division separates sister chromatids of each chromosome.

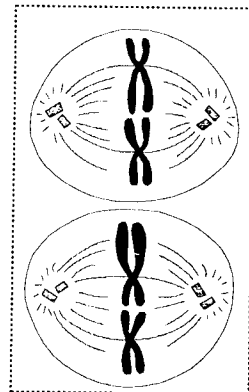
*Prophase II*

- If the cell entered interkinesis, the nuclear envelope and nucleoli disperse.
- Spindle apparatus forms and chromosomes move toward the metaphase II plate.



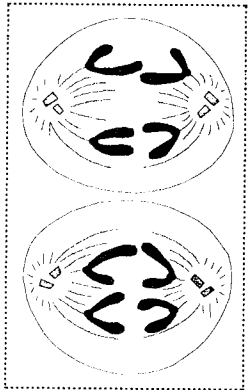
*Metaphase II*

- Chromosomes align singly on the metaphase plate.
- Kinetochore of sister chromatids point toward opposite poles.



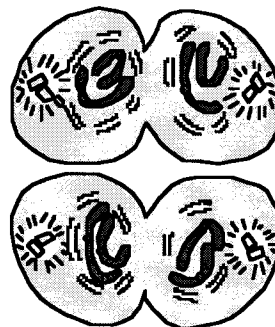
*Anaphase II*

- Centromeres of sister chromatids separate.
- Sister chromatids of each pair (now individual chromosomes) move toward opposite poles of the cell.



*Telophase II and Cytokinesis*

- Nuclei form at opposite poles of the cell.
- Cytokinesis occurs producing four haploid daughter cells.



Haploid daughter cells



### 1. Mitosis and meiosis compared

Spending class time on a comparison of mitosis and meiosis is really worth the effort. It not only brings closure to the topic, but also provides an opportunity to check for understanding. One check is to ask students to identify unlabeled diagrams of various stages in mitosis and meiosis. The ability to distinguish metaphase of mitosis from metaphase of meiosis I, is particularly diagnostic of student understanding.

If you are fortunate enough to have video capability in your classroom, you can show moving sequences of mitosis and meiosis. The fact that these are dynamic processes involving chromosomal movement is not a trivial point, but is often lost in the course of a lecture where the only visuals are drawings or micrographs.

Though the processes of mitosis and meiosis are similar in some ways, there are some key differences (see Campbell, Figure 13.7):

- *Meiosis is a reduction division.* Cells produced by mitosis have the same number of chromosomes as the original cell, whereas cells produced by meiosis have *half* the number of chromosomes as the parent cell.
- *Meiosis creates genetic variation.* Mitosis produces *two* daughter cells genetically identical to the parent cell and to each other. Meiosis produces *four* daughter cells genetically different from the parent cell and from each other.
- *Meiosis is two successive nuclear divisions.* Mitosis, on the other hand, is characterized by just one nuclear division.

Comparison of Meiosis I and Mitosis		
	Meiosis I	Mitosis
Prophase	<i>Synapsis</i> occurs to form tetrads. <i>Chiasmata</i> appear as evidence that crossing over has occurred.	Neither synapsis nor crossing over occurs.
Metaphase	Homologous pairs (tetrads) align on the metaphase plate.	Individual chromosomes align on the metaphase plate.
Anaphase	Meiosis I separates pairs of chromosomes. Centromeres do <i>not</i> divide and sister chromatids stay together. Sister chromatids of each chromosome move to the <i>same</i> pole of the cell; only the homologues separate.	Mitosis separates sister chromatids of individual chromosomes.  Centromeres divide and sister chromatids move to <i>opposite</i> poles of the cell.

Meiosis II is virtually identical in mechanism to mitosis, separating sister chromatids.

## III. Origins of Genetic Variation

### A. Sexual life cycles produce genetic variation among offspring

Meiosis and fertilization are the primary sources of genetic variation in sexually reproducing organisms. Sexual reproduction contributes to genetic variation by:

- Independent assortment
- Crossing over during prophase I of meiosis

- Random fusion of gametes during fertilization

### 1. Independent assortment of chromosomes

At metaphase I, each homologous pair of chromosomes aligns on the metaphase plate. Each pair consists of one maternal and one paternal chromosome.

- The orientation of the homologous pair to the poles is random, so there is a 50-50 chance that a particular daughter cell produced by meiosis I will receive the maternal chromosome of a homologous pair, and a 50-50 chance that it will receive the paternal chromosome.
- Each homologous pair of chromosomes orients independently of the other pairs at metaphase I; thus, the first meiotic division results in *independent assortment* of maternal and paternal chromosomes (see Campbell, Figure 13.8)
- A gamete produced by meiosis contains just one of all the possible combinations of maternal and paternal chromosomes.

*Independent assortment* = The random distribution of maternal and paternal homologues to the gametes. (In a more specific sense, assortment refers to the random distribution of genes located on different chromosomes.)

- Since each homologous pair assorts independently from all the others, the process produces  $2^n$  possible combinations of maternal and paternal chromosomes in gametes, where  $n$  is the haploid number.
- In humans, the possible combinations would be  $2^{23}$ , or about eight million.
- Thus, each human gamete contains one of eight million possible assortments of chromosomes inherited from that person's mother and father.
- Genetic variation results from this reshuffling of chromosomes, because the maternal and paternal homologues will carry different genetic information at many of their corresponding loci.

### 2. Crossing over

Another mechanism that increases genetic variation is the process of *crossing over*, during which homologous chromosomes exchange genes.

*Crossing over* = The exchange of genetic material between homologues; occurs during prophase of meiosis I. This process:

- Occurs when homologous portions of two nonsister chromatids trade places. During prophase I, X-shaped *chiasmata* become visible at places where this homologous strand exchange occurs.
- Produces chromosomes that contain genes from *both* parents.
- In humans, there is an average of two or three crossovers per chromosome pair.
- Synapsis during prophase I is precise, so that homologues align gene by gene. The exact mechanism of synapsis is still unknown, but involves a protein apparatus, the *synaptonemal complex*, that joins the chromosomes closely together.
- Campbell, Figure 13.9 shows the results of crossing over during meiosis.

### 3. Random fertilization

Random fertilization is another source of genetic variation in offspring.

- In humans, when individual ovum representative of one of eight million possible chromosome combinations is fertilized by a sperm cell, which also represents one of eight million possibilities, the resulting zygote can have one of 64 trillion possible diploid combinations (without considering variations from crossing over!).

**B. Evolutionary adaptation depends on a population's genetic variation**

Heritable variation is the basis for Charles Darwin's theory that natural selection is the mechanism for evolutionary change. Natural selection:

- Increases the frequency of heritable variations that favor the reproductive success of some individuals over others
- Results in *adaptation*, the accumulation of heritable variations that are favored by the environment
- In the face of environmental change, genetic variation increases the likelihood that some individuals in a population will have heritable variations that help them cope with the new conditions.

There are two sources of genetic variation:

1. Sexual reproduction. Results from independent assortment in meiosis I, crossing over in prophase of meiosis I, and random fusion of gametes during fertilization.
2. Mutation, which are random and relatively rare structural changes made during DNA replication in a gene could result from mistakes.

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